Measurement of Sanitary Ventilation*†

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ABILITY to modify man's environment is not confined to the enhancement of comfort, convenience, or even safety but extends to the prevention of disease and the promotion of health. By supplying pure water and pure food, the sanitary engineer has, in many communities, almost eliminated intestinal infection. Is it unreasonable to hope that, when air-borne infection is better understood, diseases conveyed through the respiratory tract may likewise be reduced through the provision of pure air supplies?

Experimental evidence has accumulated during the past few years which brings this possibility within the realm of the engineer.[1] It has been shown:

1. During coughing and sneezing, minute droplets containing microörganisms from infected surfaces may be ejected into the air.[2]
2. Most of these droplets are sufficiently small to evaporate before they can settle to the ground, leaving suspended in the air minute residues.[3]
3. These nuclei, in which the microörganisms remain viable for considerable periods, may drift in air currents as would particles of cigarette smoke.[4]
4. The air breathed commonly by the various persons congregated in a room or other enclosed space can thereby transfer these organisms from one person to another and plant them upon the susceptible tissues of the respiratory tract.[1]

The engineer may, therefore, proceed upon the assumption that drifting particles arising from common occupancy of enclosed spaces constitute a hygienic hazard, which may be reduced through the elimination of the microörganisms thus suspended in air. Where individual supplies of air can be furnished to each person, the problem of air-borne infection disappears. Blackfan and Yaglou [5] report spectacular reduction in acute and chronic infection of premature infants, chiefly respiratory, by the installation of a separate air-conditioned supply to wards for premature infants. The Chapple incubator [6] by providing an individual supply of pure outside air to each infant attains this theoretical ideal, for even the nurse is excluded from the child's atmosphere. Whether the principle of the individual air supply can be profitably prolonged beyond the premature into the normal life span is a problem of hygiene as well as engineering. The practicability of a cabinet cubicle for infant care in nurseries is now being studied by Dr. Chapple in the Laboratory of Air Hygiene at the Children's Hospital, Philadelphia.

In general, however, the engineer must provide for common occupancy of enclosed spaces. The magnitude

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of this hazard depends upon the degree of confinement of the air common to many persons, or rather upon the concentration of the contaminating nuclei, which varies directly with the number of persons occupying a given volume of air (and their specific infectivity), and inversely with the dilution either with pure air from without or with any other equivalent means of elimination of the microörganisms, such as precipitation, filtration, washing, physical or chemical disinfection. As Colvin has said,

> The fundamental factors in prevention or control of droplet infection become evident. Dilution of the droplets by air space or change of air provide the barrier, *i.e.,* proper space for each one, especially in sleeping, and proper ventilation.[7]

Sanitary ventilation may, therefore, be defined as the rate at which microorganisms are vented; or as the proportional air replacement which would remove the equivalent number of microorganisms eliminated by any other means.

METHODS OF MEASURE OF EQUIVALENT VENTILATION

With the modern technic of sanitary air analysis,[8] the equivalent air replacement can be simply determined. A diluted culture of the test organism is thrown into the air by an atomizer (Figure I) which may be designated the infector. Following the instantaneous evaporation of the droplets, the contained bacteria remain suspended in the air like an invisible smoke. The bacterial concentration may be determined by the air centrifuge,[9] which represents a mechanical infectee. The specific technic is contingent upon the dimensions involved.

B. coli is a convenient test organism: it is harmless; it is easy to culture, and we have in eosin-methylene blue agar a selective medium in which *B. coli* grows readily but which is in-

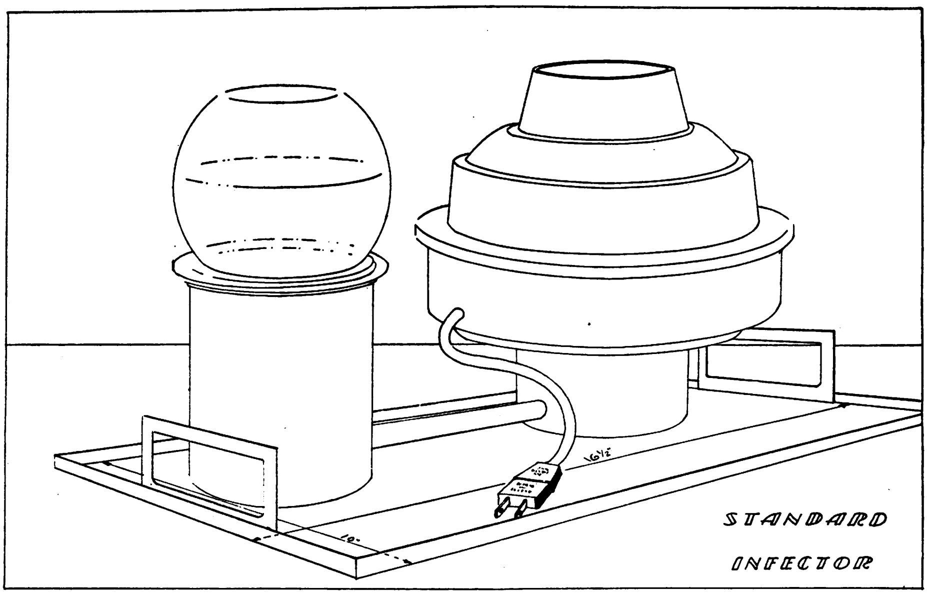

FIGURE I—Atomizer adapted from special assembly of humidifier by William Feldermann, American Gas Accumulator Co., Elizabeth, N. J.

hibitive to other organisms in the air (in these tests, contaminants); on this medium the colonies are readily counted[10]; it grows singly; it is not a normal inhabitant of the air, and one can be sure that the organisms recovered by the centrifuge were put there by the atomizer.

It becomes possible, therefore, by a suitable technic to measure directly the degree to which an infector at any point in a confined space infects an infectee at any other point under given conditions of ventilation. By comparing these measurements under varying conditions of ventilation we are provided with a quantitative instrument for measuring sanitary ventilation as defined above.

Two general methods are described which make it possible to study specifically the conditions which facilitate or impede the passage of infection from infector to infectee and to determine the efficacy of any means for preventing or reducing such passage of microorganisms. These measurements may be compared to the effect produced by removing from the confined space a given proportion of the volume of air in a chosen unit of time, the removal rate giving a unit of equivalent ventilation. Replacement of the confined air by outside air or air from other parts of the building by natural or artifical means, or removal or destruction of microörganisms within the air, all can be expressed in terms of equivalent ventilation.

I. Method of the Die-away—The simplest method for determining the ventilation rate is to build up within a room a desired bacterial concentration by atomizing a diluted liquid culture of the test organism; the atomizer is then turned off and consecutive samples of the air are taken.[8] Since with uniform ventilation the number of organisms removed in a small unit of time is proportional to the number present, that is:

$$dN = -KNdt$$

it follows that

$$\log_e \frac{N}{N_o} = -Kt \text{ and } N = N_o e^{-Kt}$$

The difference between the logarithms of two counts divided by the elapsed time between the two samples gives the value K. The value K as thus determined by using natural logarithms becomes the rate at which microörganisms are being vented and therefore a measure of sanitary ventilation. If we express time in minutes K then represents the proportional air replacement per minute which would vent an equal number of organisms and therefore becomes a unit of equivalent ventilation. Multiplied by 60, the equivalent turnovers per hour as understood by the ventilating engineer can be ascertained.

Since K is more conveniently calculated by common logarithms, the K so determined must be multiplied by 2.3 to obtain the equivalent ventilation as given above, or the K is multiplied by 138 (2.3 x 60) to obtain the turnovers per hour. The working rule for obtaining equivalent sanitary ventilation becomes: *the number of overturns per hour is equal to 138 times the difference in the logarithms of two counts divided by the elapsed time in minutes between the two counts.*

II. Method of Equilibrium—If an infector contributes bacteria to the air at a uniform and constant rate, the number within the space will increase until the number removed will equal the number added in a unit of time. If the number removed, as given by the *method of the die-away,* is a constant proportion of the number present, it follows that when the rate of removal multiplied by the number present equals the rate of addition, equilibrium will have been reached. The concen-

TABLE I

Laboratory of Sanitary Ventilation for the Study of Air-borne Infection
Routine Test of Sanitary Ventilation, 1/10/38

Infector on continuously from 3:27 P.M. to 4:27 P.M., atomizing a 22 hour culture of *B. coli,* diluted to 5 per cent

	Tube	Time	*Temp.* ° *F.*	*R.H.* %	*Counts* (*Logarithm of*)					*Overturns per Hour*
Equilibrium: 12" quartz mercury Geissler tube on at 3:32 P.M., center of room, reflected upward above eye level	I	3:33–38	69.0	47	3.7163	C/K_1	K_1/K	K_1/K	K_1	
	II	3:39–44	69.5	48	3.6379	3.3651 (asymptote)	.9859	9.7	.8410	116
	III	3:45–50	69.5	48	3.5729					
Equilibrium: therapeutic carbon arc projector,* screened through Corex D glass, throwing beam across room	IV	3:52–57	69.5	50	3.6091	C/K_2	K_2/K	K_2/K	K_2	
	V	3:58–03	69.5	52	3.8587	4.0840	.2670	1.9	.1647	23
	VI	4:04–09	69.5	52	4.0840					
Equilibrium: lights off	VII	4:10–15	69.5	52	4.2781	C/K		C/K	C	
	VIII	4:16–21	69.5	53	4.3160	4.3510 (asymptote)		22,450	.1850	
	IX	4:22–27	70.0	54	4.3338					
Die-Away: lights off, infector off	X	4:28–33	70.5	52	4.0700	K			K	
	XI	4:34–39	70.5	52	3.4035	.1111			0867	11.3
	XII	4:40–45	70.5	52	3.0298	.0623				
						Av .0867				

Test room: 20′ x 20′ x 12′; 3 windows on one side, 1 on another; 3 doors on other two sides—all closed

Atomizer placed near center of 3 window side, 8′ from floor; heating radiators beneath created an up-draft; ordinary home electric fan blowing toward atomizer created a cross-draft

Centrifuge at opposite side of room from atomizer, 3′ from floor

* Note: Same lamp without Corex D filter gave in another test 537 overturns per hour

tration in the room when equilibrium is reached, therefore, is equal to C/K where C is the addition rate and K is the removal rate (given by the method of die-away).

If a ventilating factor is changed, then the new equilibrium will adjust itself in accordance with this equation, and by dividing the number per unit volume obtained under the two conditions of equilibrium, the addition factor cancels and the removal rates will vary inversely with the equilibria reached. If any removal rate has been determined by the die-away curve, removal rates obtained with other ventilating factors may be readily compared by the ratios between the equilibria obtained by test.

For example, under three consecutive conditions of ventilation we obtain equilibria C/K, C/K_1, and C/K_2 from which K_1/K and K_2/K can be obtained by division. These ratios multiplied by K, as determined by the method of the die-away, give the values of K_1 and K_2.

(In the sample test, the elapsed time between samples is 6 minutes. The counts are conveniently computed into logarithms as given in the record. The difference between logs X and XI, or XI and XII, divided by 6 gives K. Subtracting from the log of C/K, log C/K_1 and log C/K_2 gives log K_1/K and log K_2/K, from which K_1/K and K_2/K are obtained. Multiplying by K, as determined from the die-away, gives K_1 and K_2. Multiplying K, K_1, and K_2 by 138 gives overturns per hour.)

The time required for an equilibrium to be reached is theoretically infinite but under practical conditions can usually be obtained within a reasonable period. It is possible, however, to express the number obtaining at any time after the commencement of the addition by the formula:

$$P = \frac{C}{K}\,(1 - e^{-Kt})$$

which reduces at zero time to zero and approaches an asymptote C/K as the time is prolonged to infinity. It will be further seen that the greater the value of K, the more rapidly does the number approach this asymptote.

It may be inconvenient to solve for the value of C/K by determining the shape of this curve, and yet the time required to approach the practical equilibrium may be longer than desired in making a test. The accurate determination of three points at equal intervals, as by taking three consecutive samples, permits the computation of C/K. Bacteriologic analyses ordinarily are not sufficiently precise to locate the asymptote accurately, but this relationship assists in the graphic location within the accuracy demanded in practical tests. It is characteristic of this curve, whether increasing or decreasing, that the product of the extremes minus the square of the mean divided by the sum of the extremes minus twice the mean gives the asymptote C/K. Thus if x, y and z are tube counts of three consecutive air samples taken with equal intervals between (see sample test), then:

$$\frac{xz - y^2}{x + z - 2y} = \frac{C}{K}$$

(In the example, counts I, II and III can be substituted for x, y and z, and so also can counts VII, VIII and IX. When, however, the formula is applied to counts IV, V and VI, the deviation of the count of one tube destroys the natural sequence for the solution is found by inspection to be unreasonable. The equilibrium is therefore assumed to be reached with count VI, although a more experienced judgment might apply a graphic correction.)

Because of individual variation in death rate of organisms in the same culture, and other technical factors, the technic must be standardized as far as possible to assure closely comparable results. The dimensions given by this typical test have been found by practical experience to yield reproduceable results.

BACTERIAL VENTILATION BY ULTRA-VIOLET IRRADIATION

A. Irradiation of Recirculated Air—The irradiation of recirculated air constitutes a simple case of bacterial ventilation by means of ultra-violet light. If the efficiency of such ventilation is determined by samples taken within the recirculation system before and after irradiation, the fraction of the bacteria removed represents the fraction of the recirculated air which may be assumed to replace by pure air the contaminated air of the room. Equivalent sanitary ventilation is thus limited by the rate of recirculation. If only 10 per cent of the air is recirculated per minute, the highest equivalent ventilation by any system of purification or by supplying entirely fresh outside air would be 6 turnovers per hour. Compared with the sanitary ventilation obtainable by treatment of the whole volume of air of occupied spaces (discussed under B and C and D) this fractional method of replacement of room air with pure or purified air by mechanical means, hitherto available to the ventilating engineer, is completely out of range. (In the sample test (Table I) a ventilating equivalent of 116 turnovers per hour was easily obtained, and other routine tests could be selected showing several thousand turnovers per hour.)

In special cases, such as railroad cars,* the rate of recirculation may be as high as 20 turnovers per hour, and therefore the irradiation of the recirculated air provides a feasible method of sanitary ventilation, especially since the occupancy load is high and usable space is greatly restricted.

B. Direct Irradiation of Room Air—In the previous case the change in the room air is given by a percentage reduction of a percentage recirculation.

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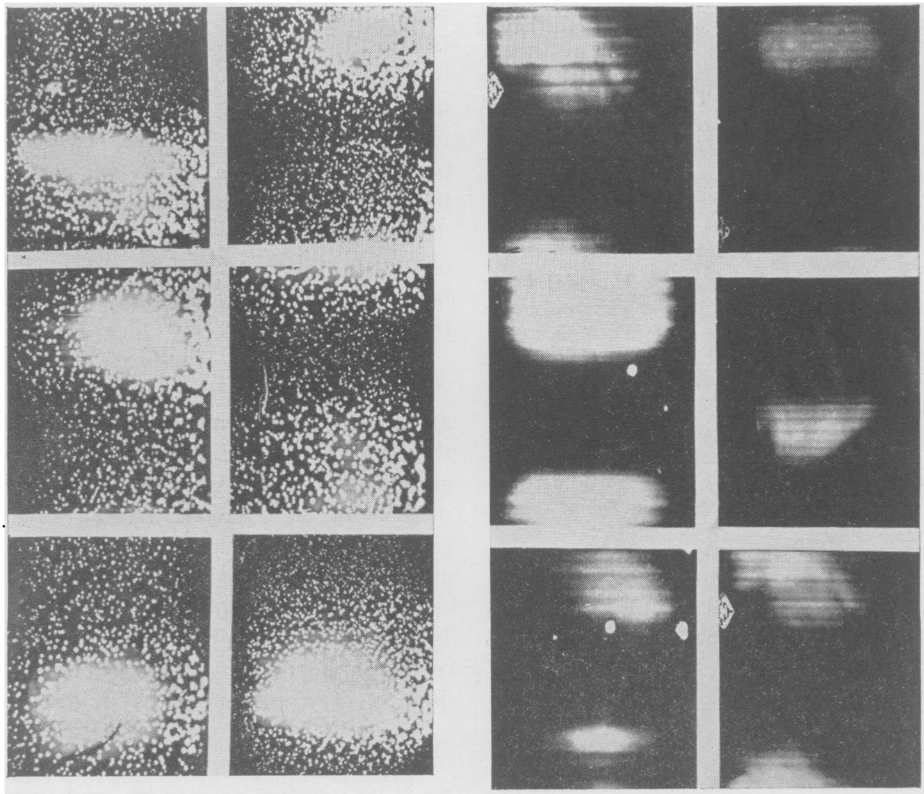
* A study of the purification by ultra-violet radiation of the recirculated air of railroad cars is being conducted in collaboration with S. M. Anderson, Research Engineer of the B. F. Sturtevant Co., Hyde Park, Mass.

Direct irradiation of the whole room is far more effective in the special instances where the eyes of the occupants can be protected. An operating room furnishes a special instance of such irradiation, since the discipline maintained permits responsible protective measures. Here reflectors containing the burners, installed in the angles where ceiling and walls meet provide general irradiation of the major portion of air in the operating room, and throw a broad beam of ultra-violet light onto the operating table.*

Such an installation may be tested by placing the infectee in the center of the room at the level of the operating table (this being the critical point of protection); by continuously infecting the air with an infector placed successively in each corner of the room;

* This type of installation has been under test by Dr. Richard Overholt, Department of Theracic Surgery, New England Deaconess Hospital, Boston, Mass., for about a year.

FIGURE II—Photographic projections of actual centrifuge tubes obtained in routine test on operating room. Tubes represent 10 minute samples with 1 minute interval between. Tubes I (omitted from picture), II and III represent build-up of bacterial concentration without lights, with infector in each of three corners successively. Lights turned on at end of each 3rd sample and off at end of each 5th sample before moving infector to another corner of room. Infector ran continuously throughout test.



Tubes II *Tubes III*
LIGHTS OFF

Tubes IV *Tubes V*
LIGHTS ON

and testing each location of the infector with the lights on and the lights off. The ratio of the equilibrium counts obtained with the lights off and the lights on then gives a measure from which the sanitary ventilation attributable to the lights can be calculated. Their power actually determined under such circumstances by the method of equilibrium, appears fantastic when converted into equivalent ventilation units, and can be better illustrated than computed (Figure II).

C. Partial Irradiation — Direct irradiation applies to special cases. The general problem of the sanitary air control of schools, institutions, etc., can be solved by partial irradiation, where the space without the eye zone is directly irradiated. The irradiation of the upper air of a room may be regarded as equivalent to removing the ceiling or ventilating upward instead of by windows if the air circulation could then be comparable to that in a room. The disinfection of the air in the unirradiated zone depends upon air movement through the irradiated space, as well as upon the spatial distribution of the radiation.

Careful design, operation, and regulation, though necessary in all sanitary light installations,* are of particular importance with partial irradiation because efficiency rests primarily upon the relationships established between the irradiated and unirradiated portions of the room. The integrated product of intensity and time of exposure for all the living organisms within the space which determines the number killed,[2] mathematically predictable in ideal geometric configurations,[1] must be bacteriologically determined in the practical solution of partial irradiation. The routine test illustrates how determinations between different points with lights on and lights off can be converted into equivalent ventilation.

Until opportunities to test buildings specially designed for irradiation become available, experience gained with empirical installations must serve to establish design principles as well as guide in effective regulation.†

D. Light Barriers — Ultra-violet screens or barriers constitute another special application. The air of cubicles ‡ separated from the surrounding air of a ward by ultra-violet light screens can be tested either by placing the infector within and the infectee without (representing the protection offered the surrounding ward from a person ill within the cubicle), or by placing the infector without the cubicle and the infectee within (representing the protection offered a person within the cubicle from the surrounding ward). In each instance the bacterial tightness of the light-enclosed space is determined by the method of equilibrium.

In an isolation hospital, where a light barrier is thrown across a corridor to separate two contagious diseases,** the efficiency or bactericidal power of this barrier may be determined directly under the actual ventilating conditions in the corridor. The infector is placed on one side of the barrier and the infectee on the other, samples being taken with the lights on and off. The infector and infectee are then reversed and the test duplicated. Tests made by the method

* Studies on air disinfection are being conducted at the Laboratory of Sanitary Ventilation, Department of Bacteriology, University of Pennsylvania Medical School.

† Such experimental installations are now being tested at the Children's Hospital, Philadelphia, Pa.; the Germantown Friends' School, Germantown, Pa.; and the Marlboro State Hospital, Marlboro, N. J.

‡ Tests are now being conducted in the Laboratory of Air-borne Infection at the Henry Phipps Institute, Philadelphia, upon cubicle design, in collaboration with C. A. Erikson, of the firm of Schmidt, Garden & Erikson, consulting architect for the Cradle Society, Evanston, Ill.

** Dr. Charles F. McKhann first applied this principle to a corridor in the Isolation Unit of the Children's Hospital, Boston, Mass., and he has observed the results for about 1 year.

of equilibrium have shown that light screens can be made practically impervious to bacteria suspended in droplet nuclei and carried by ordinary ventilating currents.

SUMMARY

These examples serve to illustrate the manner in which the essential technic can be adapted to special problems. In each instance the measure of equivalent ventilation between any two points can be expressed in terms of the proportional pure air replacement throughout the whole room which would bring about the same reduction in the infection transferred from one to the other point.

CONCLUSIONS

In attempting to define bacterial ventilation in specific terms, the engineer is entitled to assume that the value of C, as indicative of the number of persons per given volume of air space represents a degree of potential infection, and to regard the value of K as indicative of the rate of reduction in this potential hazard resulting from the instruments of ventilation, and the ratio C/K an index of the relative hazard in one room as compared with another. Whether or not such an index can be correlated with epidemiological experience remains a major problem of sanitary science. Installations of ultra-violet lamps have been set up under competent and rigid medical control in order to determine the value of such measures under specific conditions, and until such conclusions are available to the engineer, he can only be guided by the bacteriological evidence. When indices of sanitary ventilation are correlated with the epidemiological data on a sufficiently large scale, the results should guide the engineer to the proper design of ventilating instruments. This may lead to a realization of our present hope that if the sanitary quality of air is controlled, reduction of respiratory disease will be accomplished.

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10. The technic of counting and recording colonies will be described in a forthcoming paper.